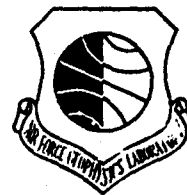AFGL-TR-81-0006
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LEVEL II

Post Burnout Thrust Measurements

EDWARD F. McKENNA

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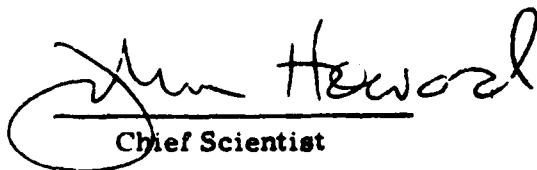
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FOR THE COMMANDER

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> Research has been conducted into the problems of avoiding collision between separated payloads and spent rocket motors due to post burnout thrust and into the problem of contamination of scientific instrumentation due to outgassing of the smoldering insulation. In order to measure this post burnout thrust, a payload instrument module was separated from an instrumented Black Brant VC Rocket in the exoatmosphere. In addition to measuring accelerations and velocities, the spent motor was observed by a TV camera on board the command attitude controlled payload module. Analysis shows that the

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payload separated cleanly from the vehicle at a relative separation velocity of
2.25 ft/sec (0.69 m/sec).   However, the residual thrust of the spent motor
overcame this differential, catching up to the payload 37 sec after separation
and continuing on a parallel velocity vector at about 3.37 ft/sec (1.03 m/sec).

Contents

Illustrations

Post Burnout Thrust Measurements

1. INTRODUCTION

Contamination of sensors by rocket outgassing has been evident to sounding rocket experimenters since the initial use of solid propellant rocket motors. Although this outgassing is usually considered to be a negligible thrust factor to the vehicle, cases of separated payloads being overtaken and passed by a spent vehicle and even colliding have been documented. To preclude any of the above happenings, AFGL has developed high velocity payload separation systems and vehicle tumble systems to achieve large spatial separation between the payload and motor.[1] While development of delta velocity and tumble systems appear to show promise in avoiding the worst separation and outgassing effects, we still have little finite data on the source of the problem, the magnitude of the post burnout thrust and outgassing of the rocket motor. This report will describe a payload developed to measure these effects and present the results from the mission.

2. MISSION DESCRIPTION

Figure 1 is a configuration sketch of the mission hardware. A motor instrument module containing sensitive chamber pressure gauges, accelerometers, and a

1. McKenna, E. F. (1976) Sounding Rocket Delta Velocity System, AFGL-TR-76-0241, AD A034435.

three-axis inertial gyro was developed to directly measure the pressure, accelera-
tion, and attitude changes of the rocket motor after burnout. A payload instrument
module also contained accelerometers to measure the post separation acceleration,
and displacement reels playing out a monofilament line between the payload and
motor to accurately measure the separation velocity. However, the key to knowing
completely what the spent rocket motor does after payload separation is to observe
it. Therefore, a television camera and two motion picture cameras were mounted
looking aft in the payload module. In order to ensure that the motor would be in the
camera's field of view, an uplink command system directed an attitude control sys-
tem to point the payload in any orientation desired by the payload controller. The
attitude control system, developed by the Space Vector Corporation, Northridge,
California controlled the payload in either an automatic position mode or a manual
rate null mode. Ground control consoles/monitors located in the blockhouse and an
outdoor mobile autotracker were a vital link in the overall system providing a
closed loop between the airborne payload and ground console operators (Figure 2).
The TV signal was transmitted on a wide band FM link while all payload instrument
data was transmitted on a 250 Kbps PCM system. A Black Brant VC rocket carried
the 650 lb (295 kg) payload 219 km above the White Sands Missile Range, New Mexico,
U.S.A. on 7 August 1979. A forward mounted parachute recovery system returned
the instruments and film for further analysis.

MOTOR INSTR. MODULE
ACCELEROMETERS
CHAMBER PRESSURE GAGES
3 AXIS INERTIAL GYRO
FM/FM TM SYSTEM

PAYLOAD INSTR. MODULE
TV CAMERA
FILM CAMERAS
ACCELEROMETERS
PCM TM SYSTEM
COMMAND/RANGING
SYSTEM

PAYLOAD A 18.805
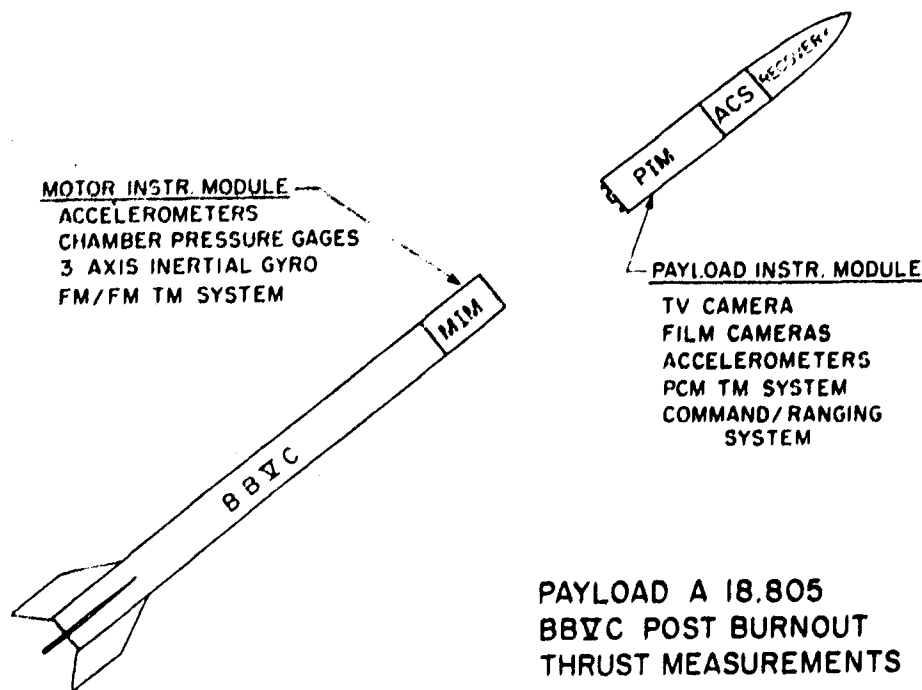BBⅤC POST BURNOUT
THRUST MEASUREMENTS
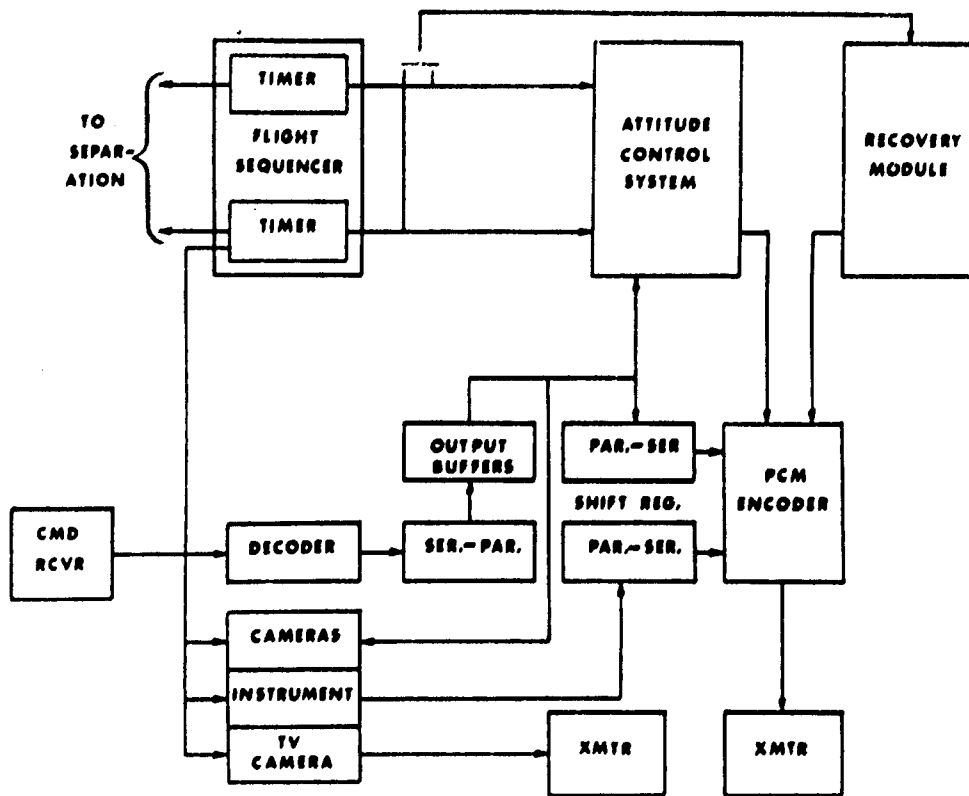
Figure 1. Mission Configuration

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Figure 2. Payload Block Diagram

3. PAYLOAD DEFINITION

3.1 Motor Instrument Module

A standard 0-1500 psi chamber pressure gauge was augmented by a 0-30 psia gauge installed in a low pressure manifold remotely opened to the motor chamber during tailoff. A -5 to +15 g longitudinal accelerometer was augmented by three-axis ± 2 g accelerometers. A Miniature Inertial Digital Attitude System recorded the vehicle's attitude after separation in order to determine the vehicle angle of attack to the velocity vector.

3.2 Payload Instrument Module

Payload separation velocity from the vehicle was measured by displacement reels in the payload playing out monofilament line attached to the motor. Shaft encoders on the reels measured the velocity within cm/second. Payload acceleration was measured by three axis ± 2 g accelerometers. An aft looking Cohu TV camera having a field of view of 70° × 52.5° provided a depth of field from

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2.7 ft (0.82 m) to infinity. Two 16 mm, 60°, field of view, 32-frame per sec ballistic cameras mounted parallel to the TV camera each carried 45 sec of Ektachrome color film. One camera was started simultaneously with payload separation, while the second was under command authority of the payload controller.

3.3 Telemetry/Command Module

An onboard flight sequencer provided preprogrammed commands, all of which, with the exception of the yo-yo de-spin, separation, and nose tip ejection were backed up with ground initiated command capability. The command module, designed by Oklahoma State University, provided security against false commands as well as decoding the command data and confirming by telemetry that the correct command was received.

PCM command data is clocked into a serial to parallel shift register, the 8-bit blocks of data are then clocked to the parallel outputs. An RC circuit on each output retains any command for approximately 1 sec after removal to prevent momentary dropouts caused by uplink RF noise. High current, high voltage output buffers are then used to interface with relays, and so on, inside the payload. Command confirmation is accomplished by clocking the data present at the output buffers into a parallel to serial shift register, converting it to a biphase-level code, and filtering and mixing it with the PCM telemetry data.

3.4 Attitude Control System

The payload attitude was controlled by a Space Vector Corporation 3-axis cold gas reaction system. Attitude reference signals were provided by a roll stabilized MIDAS analog platform within the ACS. These gyro references (that is, pitch, yaw, and roll) were established by the azimuth and elevation settings of the launcher at the moment the gyro was uncaged (Figure 3).

Signals from the gyro platform are summed with command signals selected through the relay logic. The differences, or errors, are amplified in the servo amplifiers. For pitch and yaw, the signals are distributed to the correct nozzle driver by the commutator while roll is connected directly to its drivers. The analog signals are presented to pulse width modulators where they are converted to a proportional digital signal and then conditioned (buffered) to drive a corresponding solenoid valve. Each solenoid valve is an integral part of a thruster nozzle. Therefore, torque produced by the thrusters rotates the payload changing the gyro outputs until the error signals are reduced to a null. This system had eight nozzles; two each for pitch and yaw, and four for roll. A spherical and toroidal bottle were nested together and connected in parallel to provide a plenum capacity of 750 cubic inches at a pressure of 3,000 psi. This pressure was then regulated down to

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430 psi and manifolded to the solenoid valves. Freon gas (CF_4) was chosen for its favorable specific impulse because the number of maneuvers required to perform this mission were largely unknown apart from the initial zero angle of attack and final attitude for reentry maneuvers.
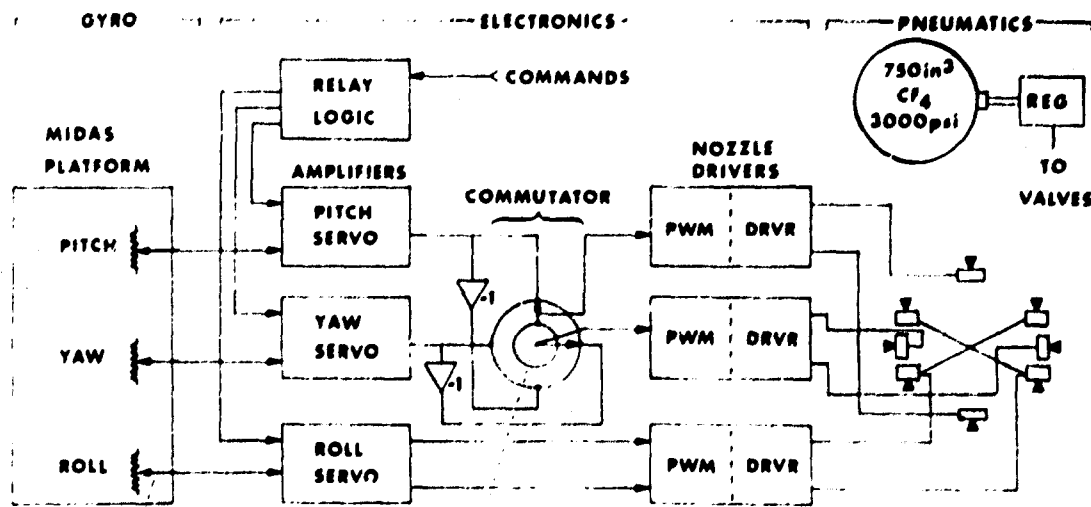

Figure 3. ACS Block Diagram

Commands from the uplink control determined the operational mode of the ACS at the discretion of the console operator. The automatic mode was a predetermined position for each of the three axes (pitch, yaw, and roll). In the manual (rate only) mode, both pitch and yaw could be selected leaving roll still in the position mode or it also could be commanded to be under rate control and vice versa. When in the rate mode, each axis could be independently commanded by actuating the joystick. Pitch and yaw rates were limited to ± 2°/sec while roll was clipped at ± 10°/second. Upon removal of a command, the payload rate would be forced to 0°/sec in the corresponding axis and held at that position until commanded otherwise.

4. GROUND CONTROL AND MONITOR SYSTEMS

The ground control and monitor system consisted of two command consoles designed by Northeastern University, a TV monitor, a PCM uplink command, ranging device (TRADAT V), and a mobile autotracker from Oklahoma State University. The command capabilities provided manual control of the attitude control system

(ACS), operation of one of the two aft-looking 16 mm film cameras, and redundant control of pre-programmed payload flight sequencer functions.[2] The autotracker transmitted command data to, and received TM data from, the payload.[3]

4.1 Command Control Consoles

One console controlled the ACS functions while the second monitored and controlled payload functions. This division of control allowed the operators to focus their attention on one aspect of the payload and not be distracted or overwhelmed with unnecessary data. The television monitor was located above and between the two consoles. An eight-position joystick and a two-position rotary switch on the ACS panel controlled the payload attitude. Momentary switches on the payload consoles were used to actuate the film cameras and other payload functions. Both consoles monitored and displayed certain critical functions such as T-time, yaw limit warning, and ACS gas pressure in addition to their own relevant monitors.

4.2 ACS Console Commands

The ACS console controlled the following eight functions:
(1) ACS to rate control,
(2) Pitch up,
(3) Pitch down,
(4) Yaw left,
(5) Yaw right,
(6) Disable roll control,
(7) Roll clockwise,
(8) Roll counterclockwise.

Pitch and yaw were actuated by the center-off plus four-position joystick. Roll was controlled by a center-off rotary switch. Illuminated, alternate position latching, pushbutton switches were used to select rate-position (1) and roll enable/disable (6) modes. The joystick and rotary switches were active only when enabled by selecting the manual rate modes and inactive in the preprogrammed position mode. The system was designed to revert to a pre-programmed position if there was a failure in the command link. The mode selection at any time during the flight was at the discretion of the operator.

2. Morin, R. L. (1979) Command Control Consoles for Sounding Rocket Payloads, AFGL-TR-80-0019, AD A084097.

3. Fike, R. M. (1979) TRADAT V Microcomputer Based Trajectory System, AFGL-TR-80-0012, AD A083074.

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4.3 ACS Console Monitors

Digital displays derived from the payload TM signals indicated payload attitude in degrees and rates in degrees/second. The remaining ACS gas pressure was displayed as a percentage on four LED's, 100%, 75%, 50%, and 25%. The critical limit of 25% caused all four LED's to flash on and off indicating to the operator that a maneuver to reentry attitude should be considered. A yaw position warning indicator would flash if ± 60° was exceeded. The MIDAS platform is limited to a ± 85° in yaw position; however, the ± 25° difference was used as a buffer to allow the operator time to react.

4.4 Payload Console Commands

Control of the film camera was the primary function of this console. Four other commands (ACS yaw hold, ACS position control, television camera on, and timer camera on) were provided as back-up in the event the sequencer failed or the trajectory was other than predicted.

4.5 Payload Console Monitors

The status of the payload commands whether initiated by the on-board sequencer or by the command system were displayed on this console. Each film camera has a 45-sec counter to display the remaining film time and six LED's to indicate the operational mode of the ACS. Unlike the ACS gas pressure indicator on the ACS console, this console displayed the pressure directly in KPSI on a digital voltmeter (DVM). Roll, pitch, and yaw null signals were also displayed on DVM's calibrated in degrees. As mentioned previously, critical monitors from the ACS console were duplicated on this console, mainly yaw limit warning and the rate/position status.

4.6 Command /Ranging System

A TRADAT V tracking system was used to transmit the commands from the control console while simultaneously providing ranging data. Each switch closure, corresponding to a command from the consoles, were logically "OR'ed" together, then clocked into a multiplexer and fed to the ranging code in TRADAT for transmission through the auto tracker. The corresponding command was sent as long as the switch remained closed and any number of available commands could be sent simultaneously. The PCM uplink command/ranging code consisted of four 16-bit minor frames of which the first 8 bits were reserved for the frame sync and the last 8 bits of the four subframes provided 32 bits of command capability.

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5. TESTING AND INTEGRATION

System integration and extensive airbearing tests were conducted at Space Vector Corporation to confirm compatibility between all ground control/monitoring equipment and the payload. The payload was installed on the airbearing fixture which allows three axes of freedom during tests. Fourteen simulated flight tests were run on the air. The console operators gained experience controlling and maneuvering the payload while observing the television and console monitors. Fixed and moving targets that simulated the booster motor were tracked successfully with three of the tests exceeding six minutes. Telemetry data recorded during the airbearing tests confirmed that all systems responded correctly.

6. FLIGHT RESULTS

6.1 Command /Control

At T+40 sec, the flight sequencer commanded the yaw memory hold event. This is basically a sample and hold function that retains the yaw attitude signal for use as a reference later in time. When the ACS was initiated 0.2 sec prior to separation (T+65.8 sec), pitch commenced to null to its predetermined flight path angle of 62° and yaw nulled to the angle retained in yaw memory (-0.62°) thereby providing a zero angle-of-attack to the velocity vector. This provided atmospheric exit stability and also insured that the booster would be in the field of view of the aft looking television and movie cameras. Roll attitude nulled to the angle established at the time of uncaging, that is 0°, by T+74 seconds. The payload remained in this attitude while observing the booster until T+95 sec when the booster caught up and narrowly missed the payload.

The manual pitch and yaw rate mode was selected and an attempt was made to track the booster. Noise on the telemetry signal in the blockhouse caused random attitude data to be displayed on the consoles for approximately 60 sec; however, the television video signal remained clean and we were able to command the payload maneuvers. Some confusion was created by the loss of attitude data and a yaw right maneuver initiated earlier continued, until by T+224 sec, the yaw attitude was 85° causing the gyro to gimbal lock with a consequent loss of reference. Post flight TM data reduction indicates that the gyro did indeed tumble in the pitch and roll axes until T+283 sec when control was reestablished. The payload was then trimmed to a horizontal reentry attitude by observing the earth's limb on the television monitor.

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6.2 Payload/Vehicle Velocities

The Black Brant VC burned out at +31 sec into flight at an altitude of 27 km. At 34 sec, the chamber low pressure manifold was opened. Pressure was reading about 0.9 psia and decaying to 0.3 psia by 51 seconds. At 65.5 sec the ACS was initiated and at 65.8 sec and 87.6 km, payload separation was initiated. The payload separated cleanly from the vehicle achieving a delta velocity of 2.25 ft/sec (0.69 m/sec). Displacement reels measured the displacement vs time between the bodies. This data paints as graphic a picture as the video display in showing the vehicle separating, catching-up, and passing the payload on a near parallel velocity vector about 3.8 ft (1.2 m) from the payload. Figure 4 shows the displacement vs time. After separation, the payload and vehicle are forced apart by the mechanical spring separation system. Maximum separation distance of 13.76 ft (5.72 m) is achieved at separation plus 17.2 seconds. The motor's post burnout velocity negates the separation velocity at this point and the vehicle starts closing on the payload, overtaking it at separation plus 37.3 sec and continuing on, achieving a peak velocity of 3.37 ft/sec (1.03 m/sec) at separation plus 47.2 seconds. At this time additional drag created by the displacement lines being forced around the edges of the payload and vehicle, decelerated the vehicle slightly so that the vehicle velocity at separation plus 65 sec, was 3.08 ft/sec (0.94 m/sec). The displacement lines were then released from the vehicle and it continued flying on ahead of the payload. At separation plus 200 sec the vehicle was observed flying about 400 ft (122 m) above the payload. Figure 5 shows the payload, vehicle, and differential separation velocities vs time.
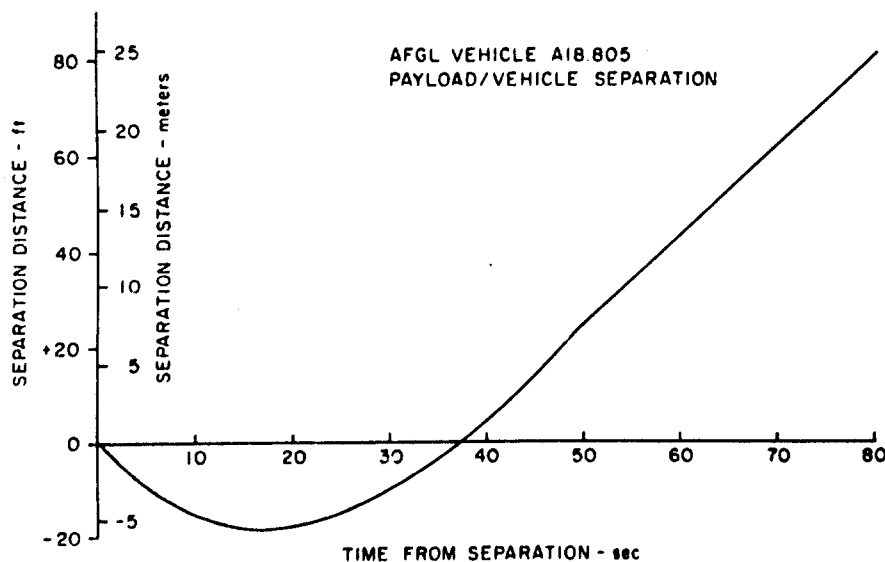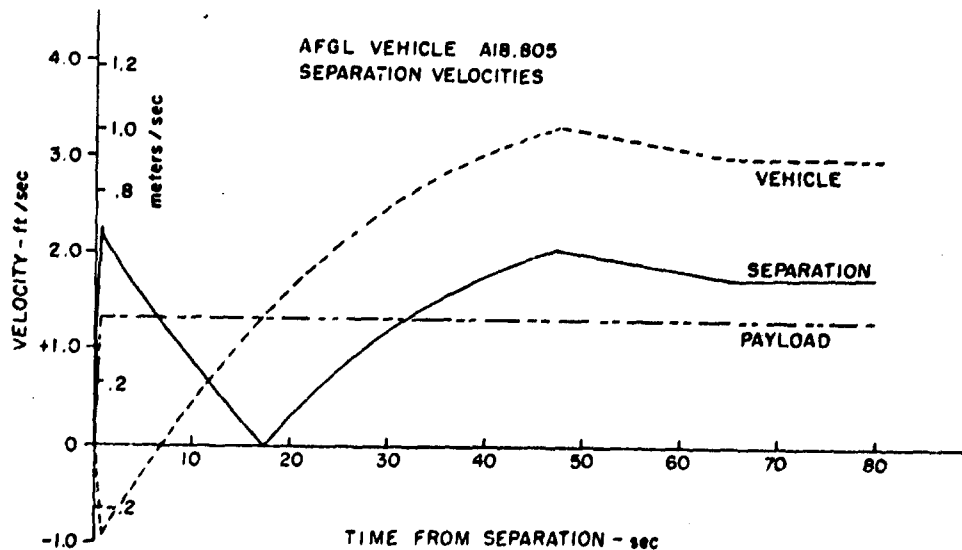

Figure 4. Displacement

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Figure 5. Velocities

6.3 Motor Thrust

Chamber pressure and vehicle acceleration data are of negligible magnitude during this time period. A theoretical thrust value was generated by simply fitting $F = ma$ into the velocity data. Figure 6 shows this curve. As experience on static firings shows that motors smolder for long periods of time after burnout, this curve should probably be a log curve asymptotic to zero. Motor attitude was relatively stable throughout its flight. At apogee, the vehicle had only tipped over about 35° from its attitude at separation and by reentry had assumed its maximum change of 70° from initial attitude.

6.4 Motor Outgassing

Considerable outgassing was observed from the spent motor long after classical burnout. Although the low chamber pressure measured would indicate that the exhaust was below nozzle critical velocity, particle velocities were considerable. The large particles were inert material. These particles were chuffed out periodically as if they temporarily blocked, then were expelled from the nozzle. Minutes after the motor had passed the payload, particles were seen streaming by.
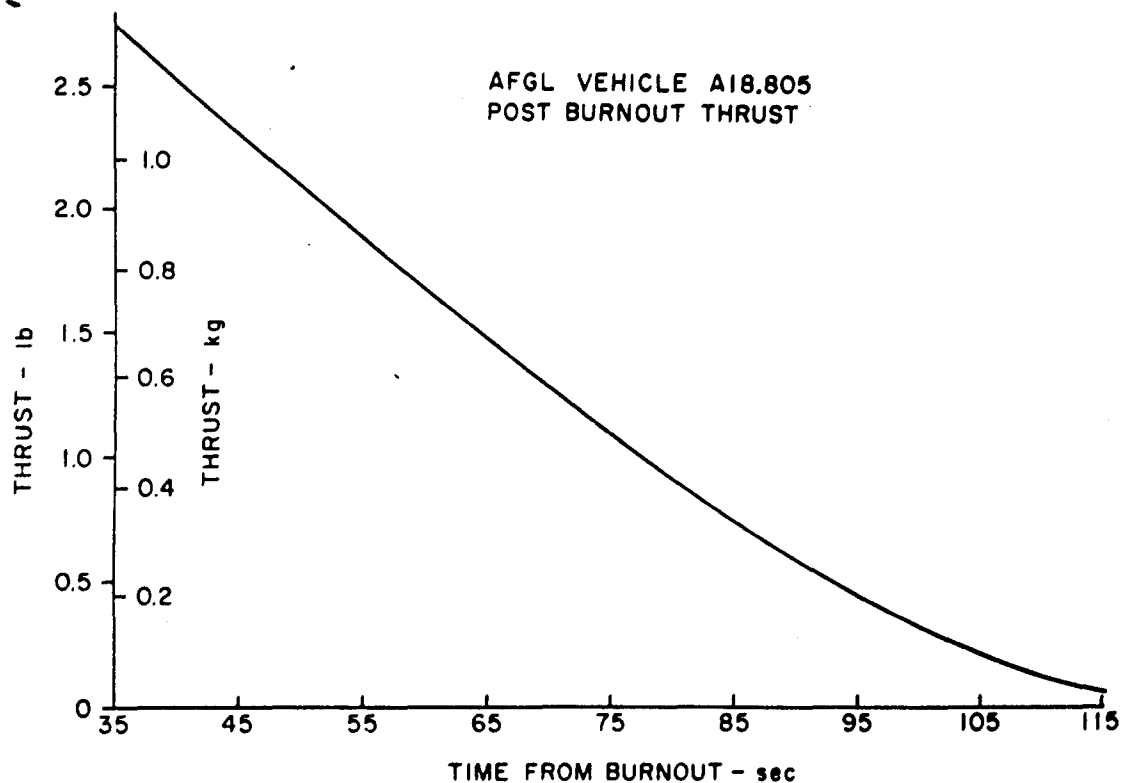
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Figure 6. Thrust

7. CONCLUSION

Solid propellant rocket motors create a possible collision catastrophe to a separated sounding rocket payload and an obvious contamination of the surrounding atmosphere. Collision between the payload and the rocket can be avoided by employing high velocity separation systems. At the Air Force Geophysics Laboratory we have established a routine policy of separating payloads at a delta velocity of not less than 20 ft/sec (6 m/sec). New separation systems for clean payloads are being designed for 40 ft/sec (12 m/sec). At one time it was considered desirable to tumble the spent rocket motor after burnout in order not to have an effective velocity vector. However it is apparent from seeing the continuous discharge from the rocket that the nozzle should never be pointed toward the payload trajectory. If the attitude of the spent motor can be controlled after separation, then it would be well to lay it over in a yaw maneuver. However as this is not often feasible, then inducing a coning action into the rocket attitude would help to reduce its incremental velocity along the payload trajectory while keeping the nozzle pointed from that direction.

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